RIVAS Final Conference "Vibrations – Ways out of the annoyance"
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Determination of dynamic soil characteristics and transfer functions to support the evaluation of the efficiency of vibration mitigation measures

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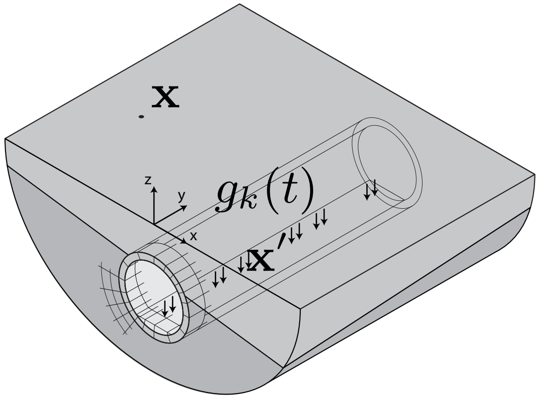
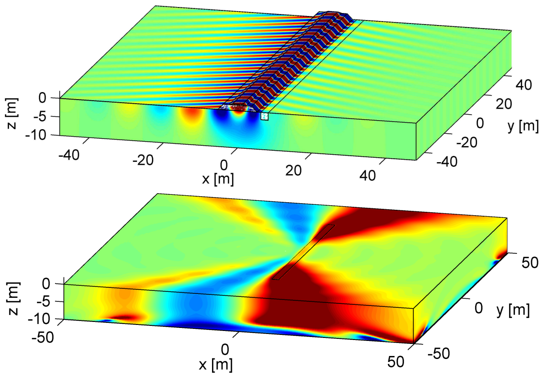
Transfer functions

Numerical prediction [Many authors]





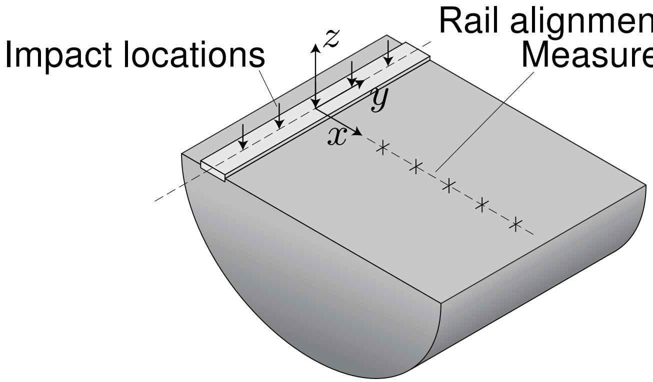
$$\mathbf{v}(\mathbf{x},t) \quad = \quad \sum_{k=1}^{n_{\mathrm{a}}} \int_{-\infty}^{t} \mathbf{H}_{\mathbf{v}}^{\mathrm{T}}(\mathbf{x}_k(\tau),\mathbf{x},t-\tau)\mathbf{g}_k(\tau)\mathrm{d}\tau \qquad (1)$$

Transfer functions

Empirical prediction (e.g. FRA and FTA [Hanson et al., 2005, 2006])

- Prediction of the ground vibration velocity level in one-third octave bands:

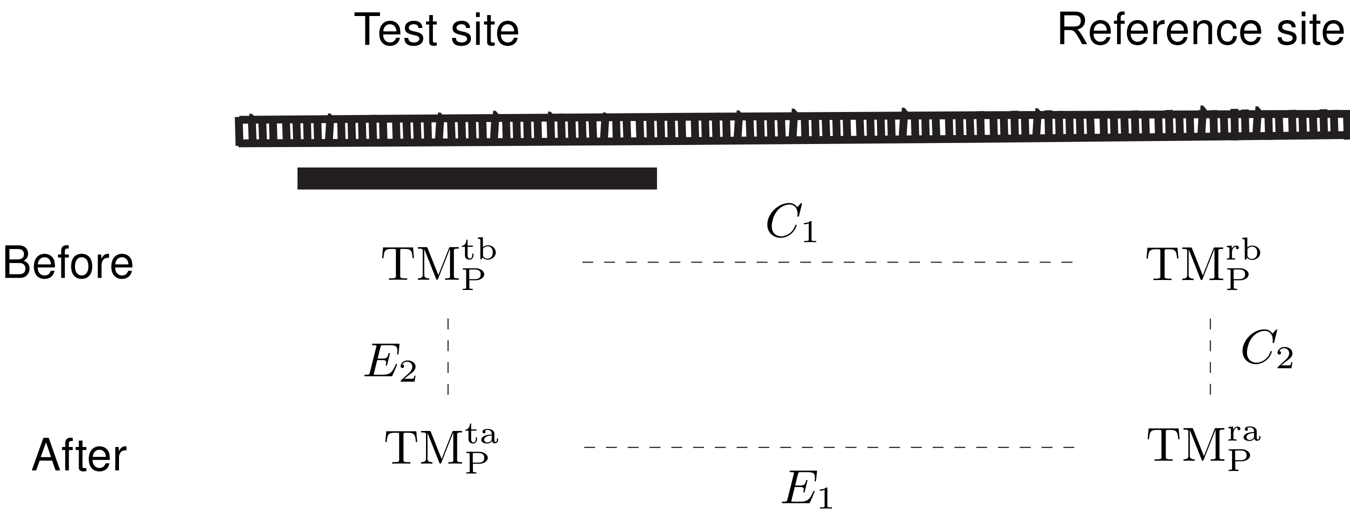
$$\mathrm{L_v} = \mathrm{L_F} + \mathrm{TM_L} \tag{2}$$



$$\mathrm{TM_L} = 10\log_{10}\left(h\sum_{k=1}^{n} 10^{\frac{\mathrm{TM}_{\mathrm{P}k}}{10}}\right) \tag{3}$$

Transfer functions

Insertion loss for vibration mitigation measures [Stiebel al., 2012]



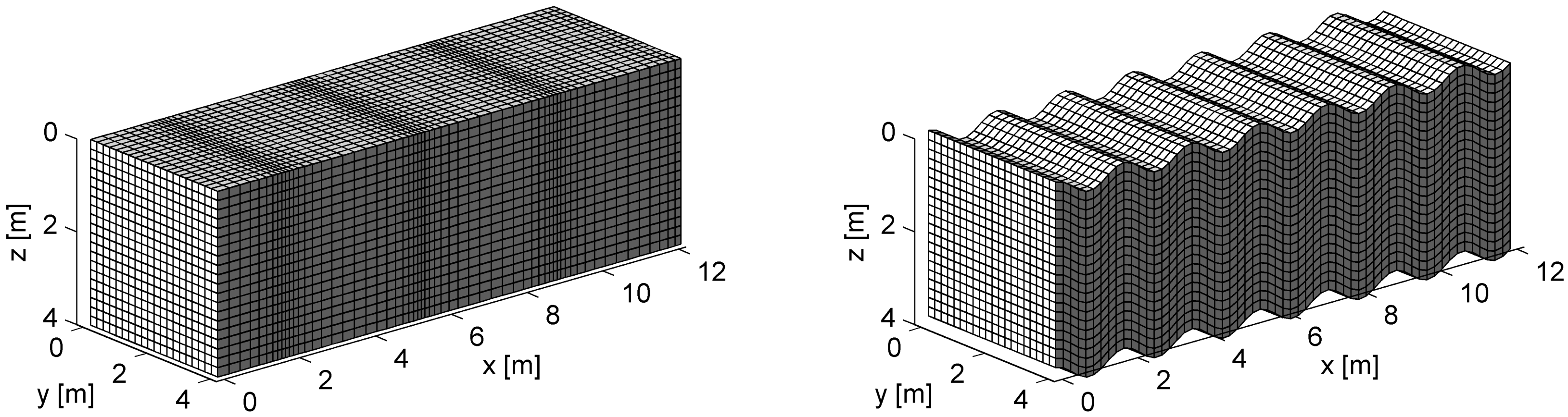
- Vibration isolation efficiency:

$$E = \underbrace{\mathrm{TM}_{\mathrm{P}}^{\mathrm{ta}} - \mathrm{TM}_{\mathrm{P}}^{\mathrm{tb}}}_{E_2} + \underbrace{\mathrm{TM}_{\mathrm{P}}^{\mathrm{rb}} - \mathrm{TM}_{\mathrm{P}}^{\mathrm{ra}}}_{C_2} \tag{4}$$

$$E = \underbrace{\mathrm{TM}_{\mathrm{P}}^{\mathrm{ta}} - \mathrm{TM}_{\mathrm{P}}^{\mathrm{ra}}}_{E_1} + \underbrace{\mathrm{TM}_{\mathrm{P}}^{\mathrm{rb}} - \mathrm{TM}_{\mathrm{P}}^{\mathrm{tb}}}_{C_1} \tag{5}$$

Dynamic soil characteristics

- (a) Dilatational and (b) shear wave in an elastic medium.



(a) (b)

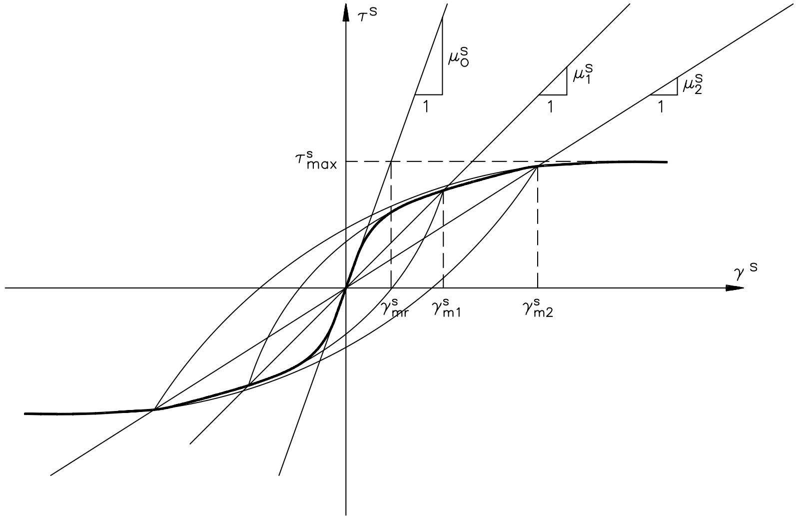
- Dilatational and shear wave velocity:

$$C_{\mathrm{p}} = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{M}{\rho}} \tag{6}$$

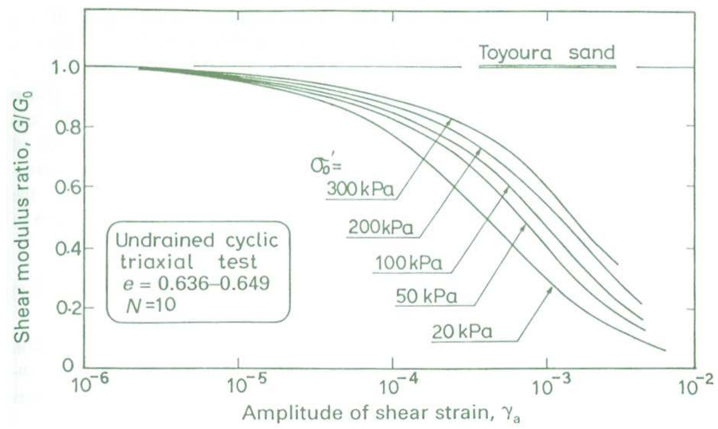
$$C_{\mathrm{s}} = \sqrt{\frac{\mu}{\rho}} \tag{7}$$

Dynamic soil characteristics

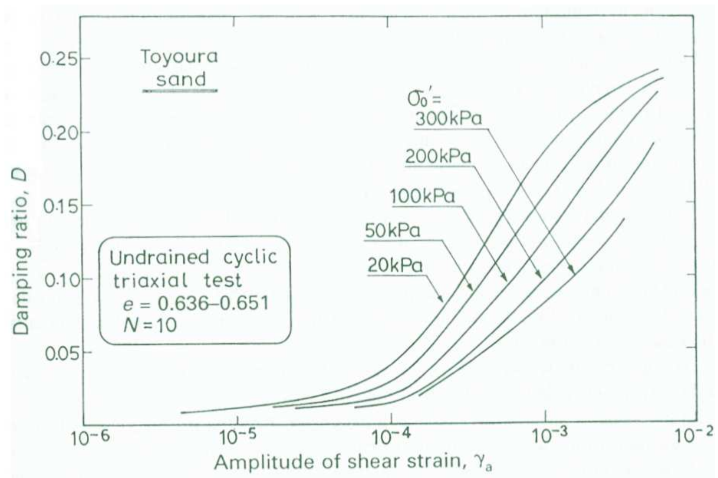
- (a) $\tau - \gamma$ curve under cyclic excitation and (b) shear modulus degradation curve and (b) material damping ratio for Toyoura sand (Kokusho, 1980):



(a)



(b)



(c)

- Material damping ratio (correspondence principle):

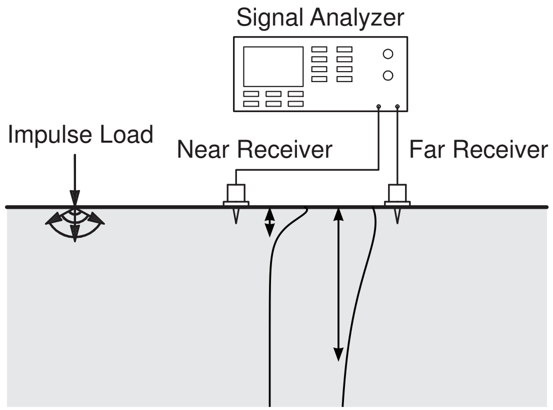
$$(\lambda + 2\mu)^\star = (\lambda + 2\mu)(1 + 2\beta_{\mathrm{p}} i) \quad (8)$$

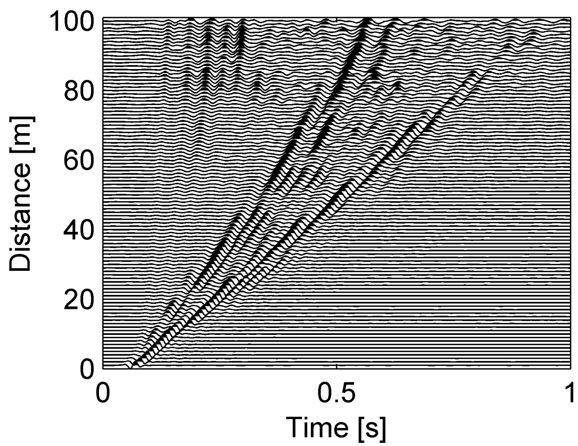
$$(\mu)^\star = \mu(1 + 2\beta_{\mathrm{s}} i) \quad (9)$$

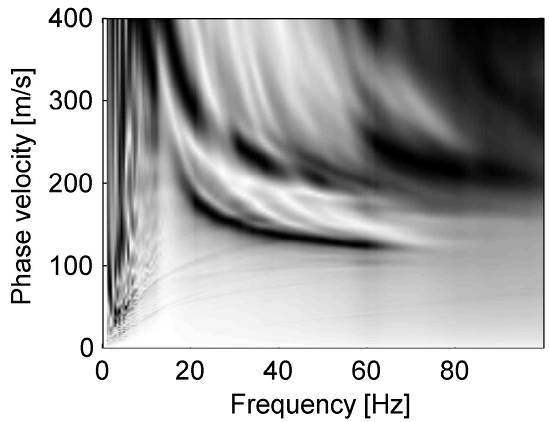
Dynamic soil characteristics

1. Archive records and test information.
   - Geological maps, results of previous geotechnical investigation.
   - Estimation of the soil layering and the dynamic characteristics of each layer.
   - Use of empirical relations cannot replace in situ or laboratory testing !
2. Classical soil mechanics tests on (undisturbed) soil samples.
   - At least one sample per soil layer; lateral sampling.
   - Mass density, void ratio, degree of saturation, plasticity index,. . . .
3. Non-intrusive geophysical tests at small strain levels.
   - Combined surface wave - seismic refraction test.
   - Measure input force.
4. Intrusive geophysical tests at small strain levels.
   - Seismic cone penetration test (SCPT).
   - Down hole or cross hole test.
5. Dynamic laboratory experiments on (undisturbed) soil samples.
   - Resonant column test.
   - Cyclic triaxial test.
   - Bender element test.

Spectral Analysis of Surface Waves







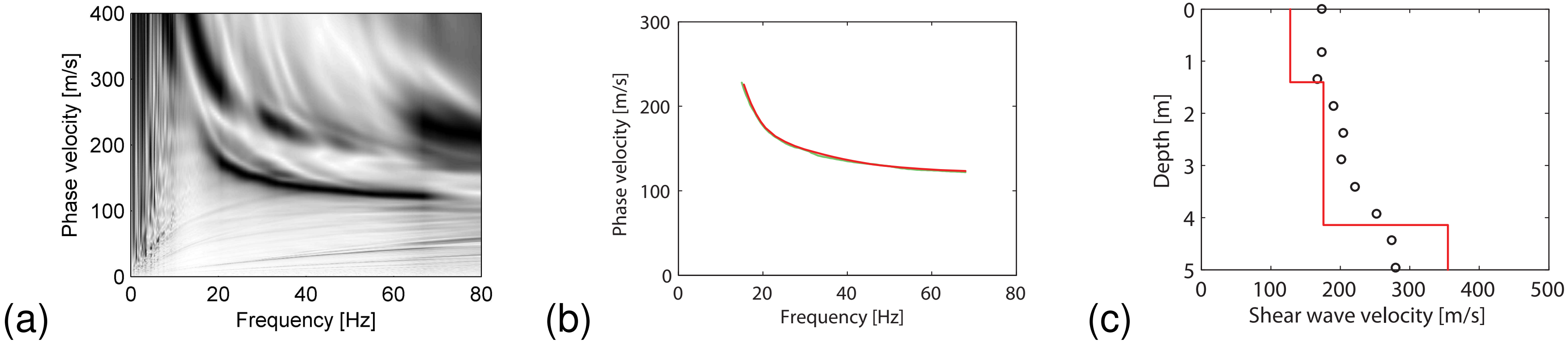
Shear wave velocity: frequency-wavenumber analysis

[Rix et al., JGGE, 2000; Lai et al., SDEE, 2002]

- Phase velocity $C_{\mathrm{R}}^{\mathrm{E}}(\omega)$ from peaks of the transfer function $\tilde{H}_{zz}^{\mathrm{E}}(k_r, \omega)$::

$$\tilde{H}_{zz}^{\mathrm{E}}(k_r, \omega) = \int_0^\infty \hat{H}_{zz}^{\mathrm{E}}(r, \omega) J_0(k_r r) r \, dr \tag{10}$$

- (a) Transfer function $\tilde{H}_{zz}^{\mathrm{E}}(k_r, \omega)$, (b) phase velocity $C_{\mathrm{R}}^{\mathrm{E}}(\omega)$, and (c) shear wave velocity profile::

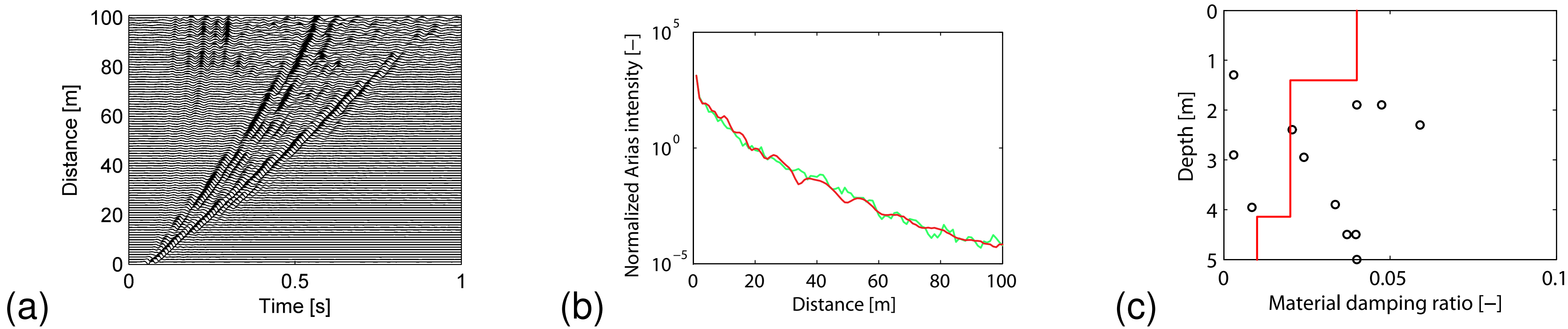


Material damping ratio: Arias intensity [Badsar, 2012]

- Arias intensity $I_{zz}^{\mathrm{E}}(r)$:

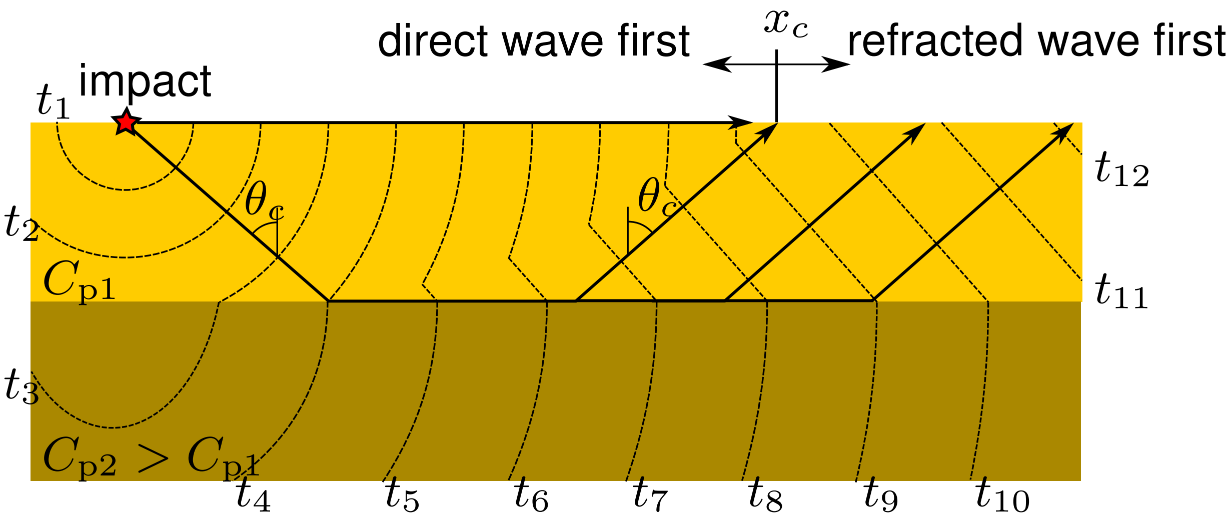
$$I_{zz}^{\mathrm{E}}(r) = \frac{\pi}{2g} \int_0^{\infty} a_z^2(r,t)\,dt \tag{11}$$

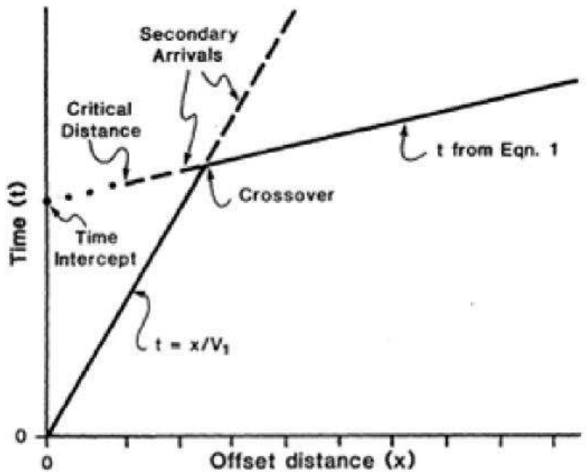
- (a) Displacement $u_z(r,t)$, (b) Arias intensity $I_{zz}^{\mathrm{E}}(r)$ and (c) material damping ratio profile:

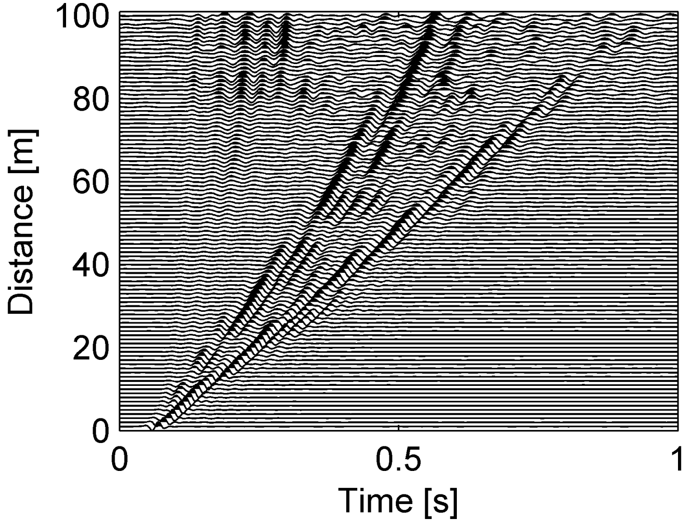


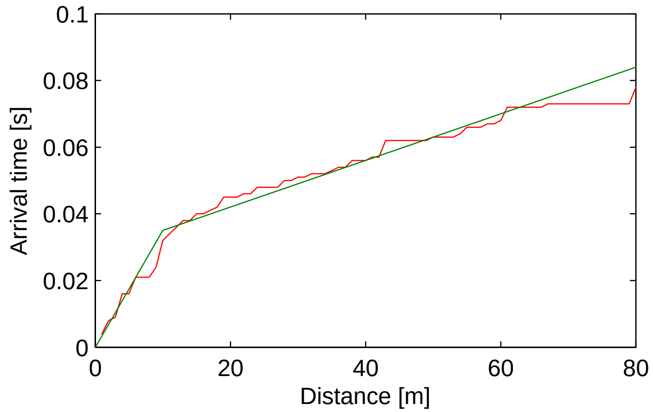
Dynamic soil characteristics

Seismic refraction test





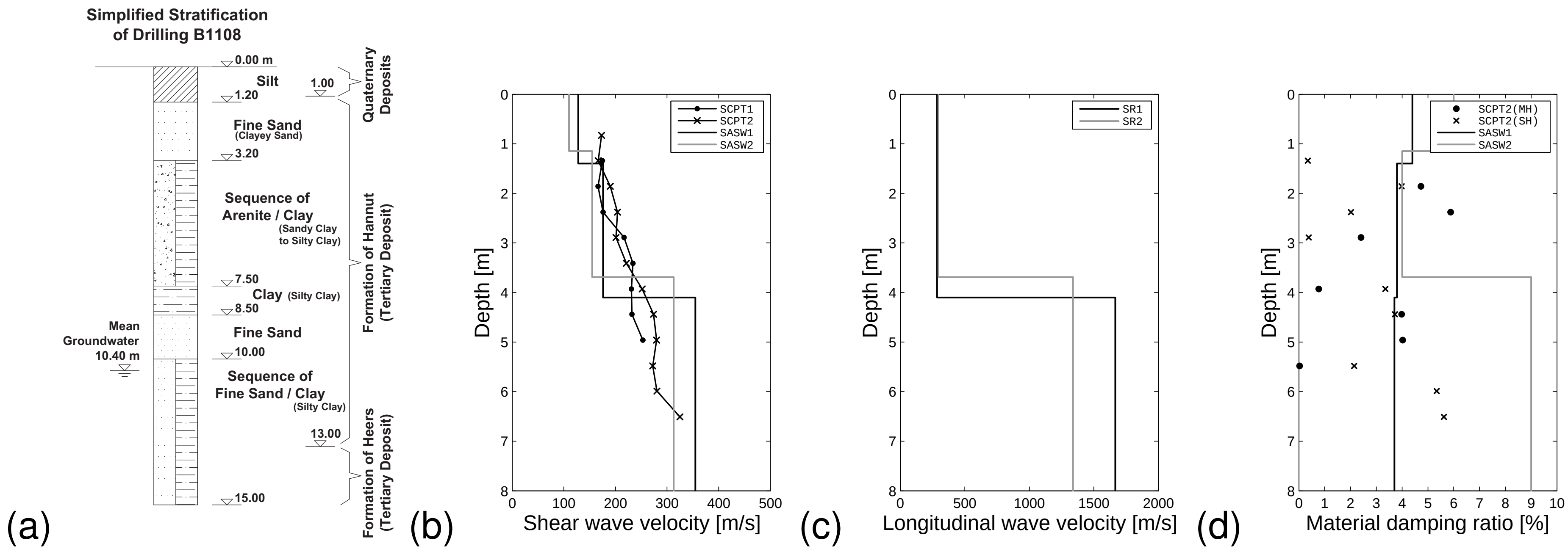




Dynamic soil characteristics

Soil profile at the site in Lincent (Belgium)

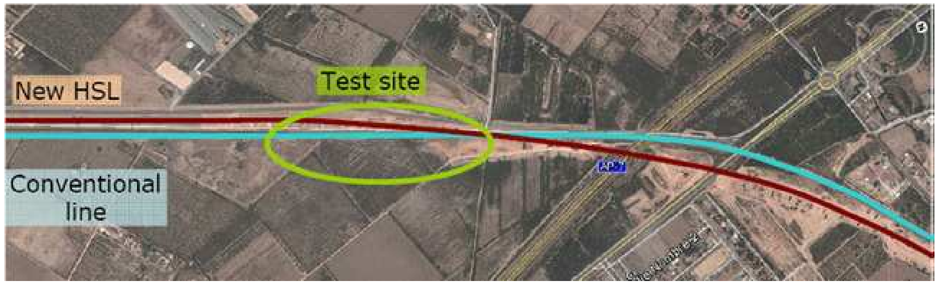
- (a) Soil stratification, (b) shear wave velocity (SASW and SCPT), (c) dilatational wave velocity (seismic refraction) and (d) material damping ratio (SASW and SCPT) profile.

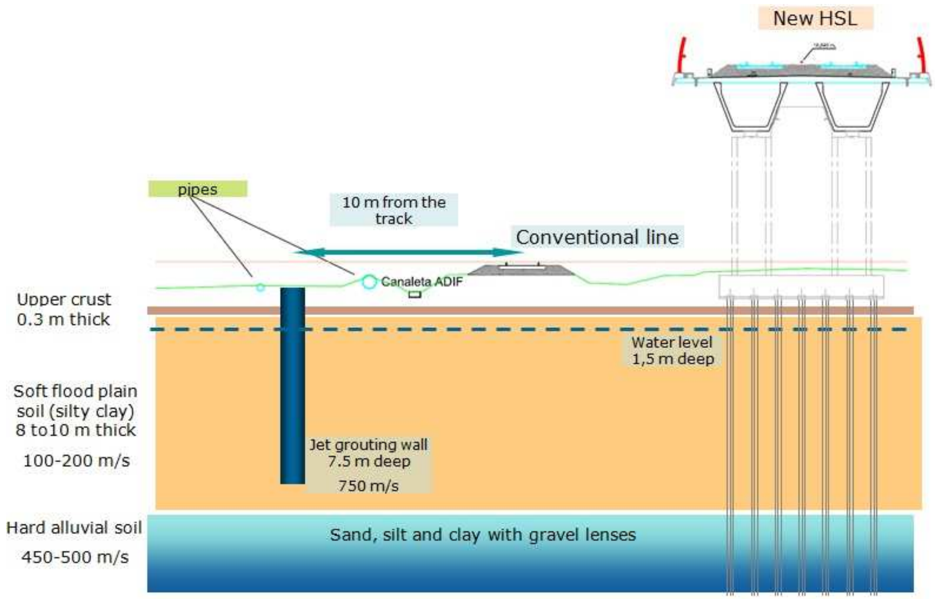


El Realengo test site

Test and reference site

- Conventional railway line (ADIF) between Murcia and Alicante.
- Low Segura river flood plain.

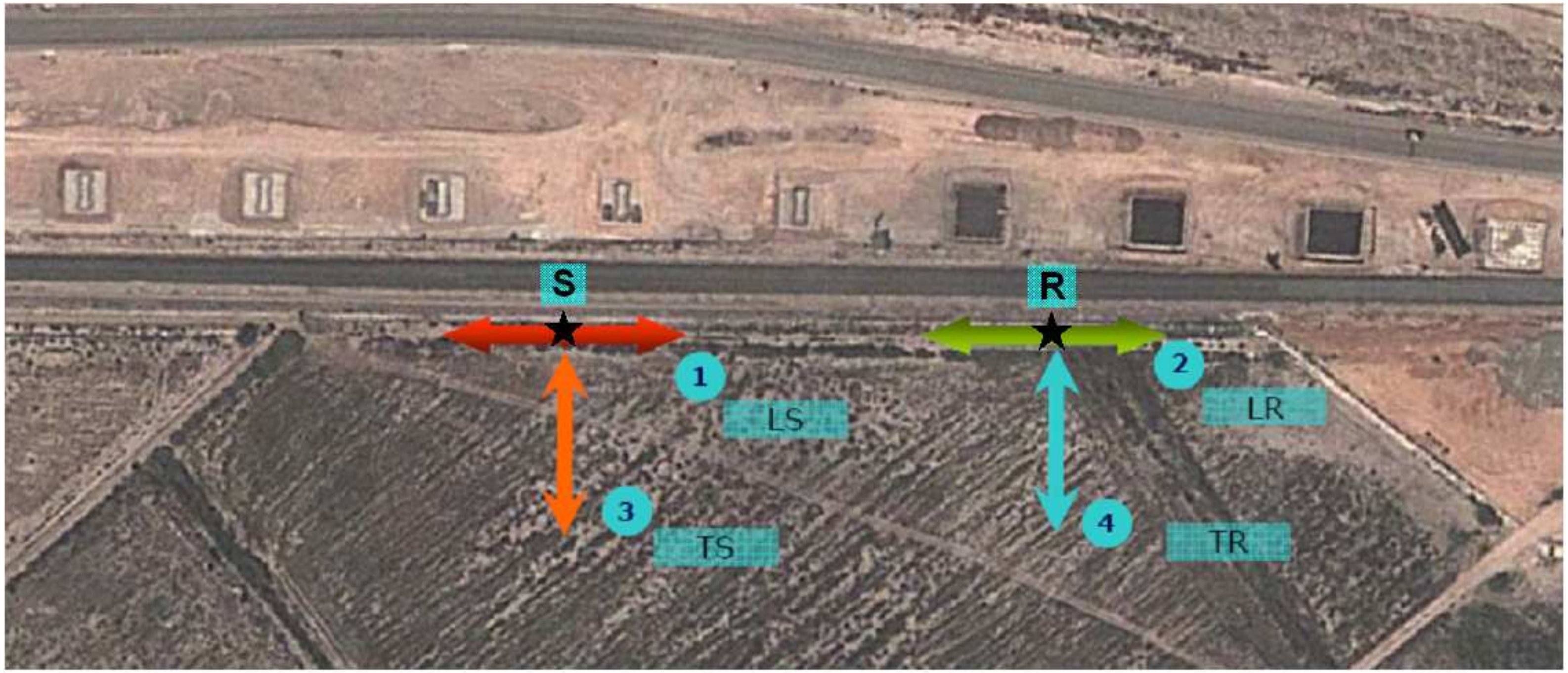




- S592 commuter train, S599 medium distance train and Talgo VI train.
- Construction of a new HST line between Madrid and Levante.
- Installation of a jet grouting wall next to track as a vibration mitigation measure.

El Realengo test site

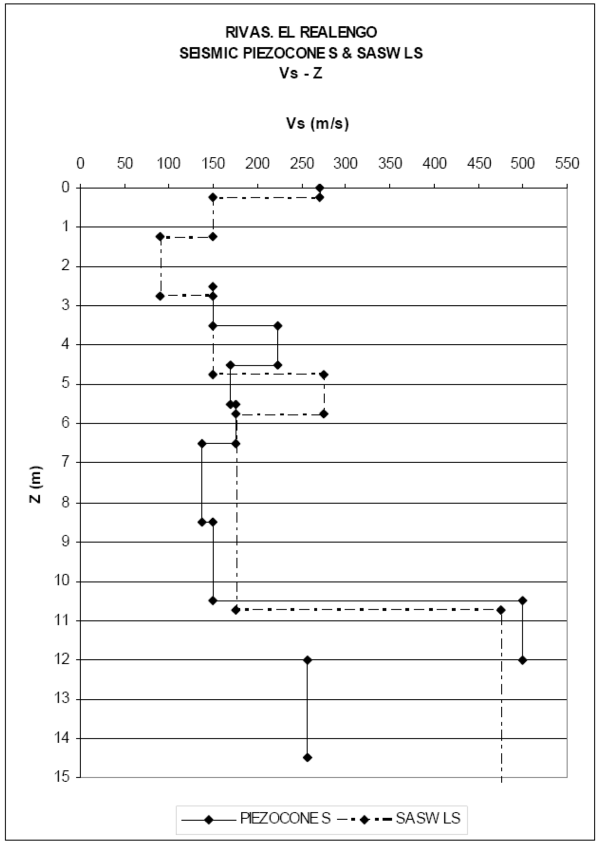
Test and reference site



Dynamic soil characteristics

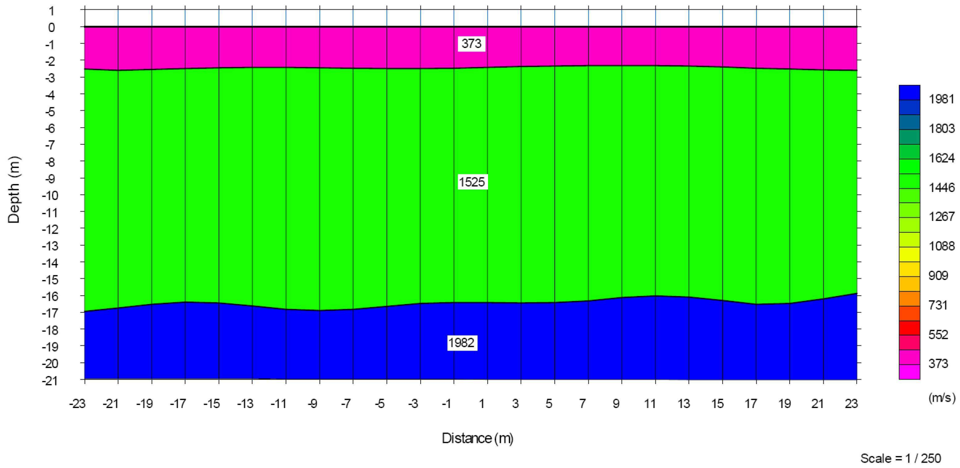
Shear wave velocity

- Spectral Analysis of Surface Waves (falling weight deflectometer, CEDEX).
- Seismic Cone Penetration Test (down-hole test, CEDEX).



Longitudinal wave velocity

- Seismic refraction test (CEDEX).



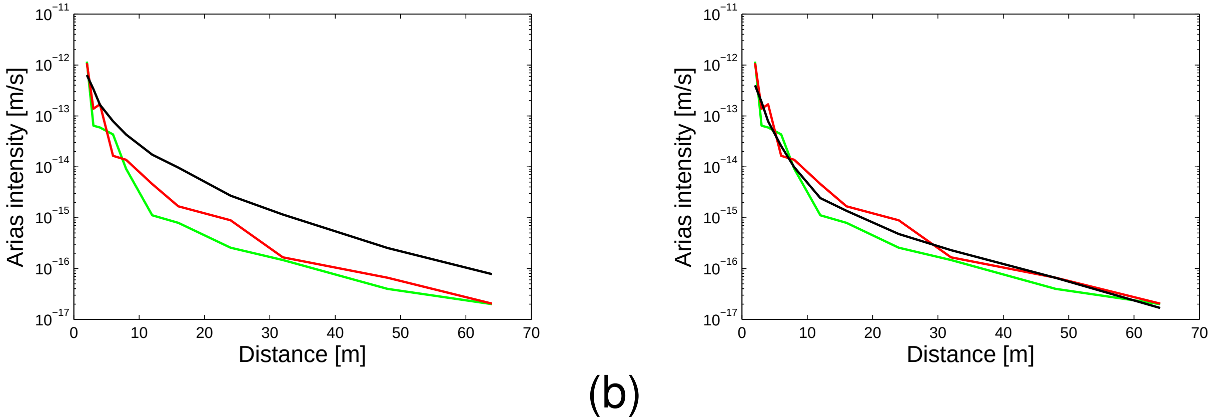
Identified soil profile

Layer	h [m]	C_s [m/s]	C_p [m/s]	β_s [−]	β_p [−]	ρ [kg/m^3]
1	0.30	270	560	0.025	0.025	1800
2	1.20	150	470	0.025	0.025	1750
3	8.50	150	1560	0.025	0.025	1750
4	10.00	475	1560	0.025	0.025	1900
5	∞	550	2030	0.025	0.025	1900

Dynamic soil characteristics

Material damping ratio

- Measured Arias intensity at the test (red line) and reference (green line) section and predicted Arias intensity (a) before and (b) after updating of the material damping ratio [Badsar, 2012].

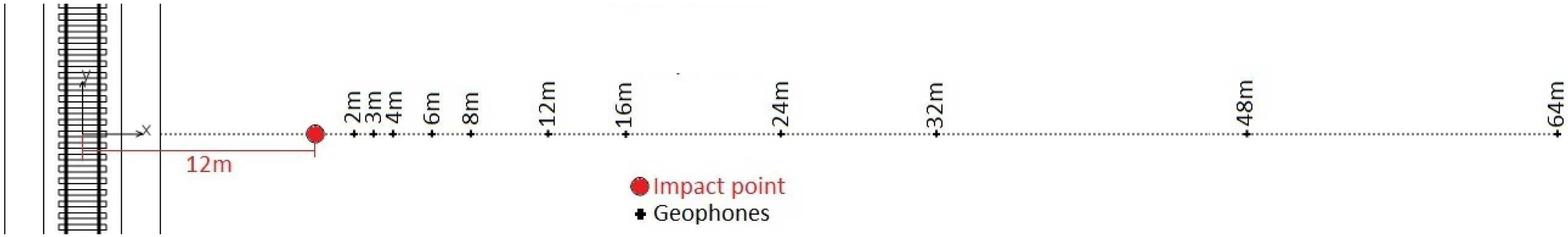


Identified soil profile (update)

Layer	h [m]	C_{s} [m/s]	C_{p} [m/s]	β_{s} [−]	β_{p} [−]	ρ [kg/m^3]
1	0.30	270	560	0.123	0.123	1800
2	1.20	150	470	0.112	0.112	1750
3	8.50	150	1560	0.014	0.014	1750
4	10.00	475	1560	0.010	0.010	1900
5	∞	550	2030	0.010	0.010	1900

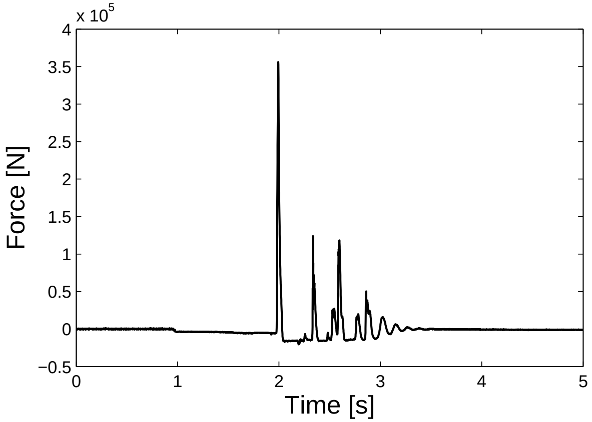
Measurement setup

- (a) Measurement setup, (b) falling weight deflectometer, (c) force during a single impact, and (d) velocity stacked for 5 impacts.

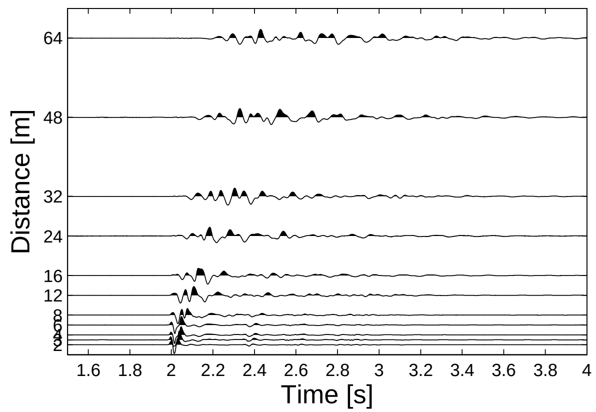


(a)

(b)



(c)

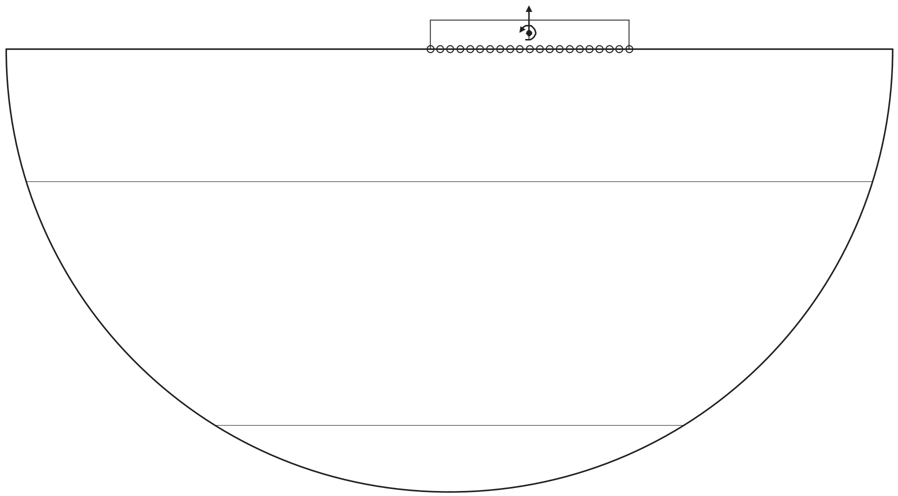


(d)

Free field transfer functions

Numerical model for benchmarking

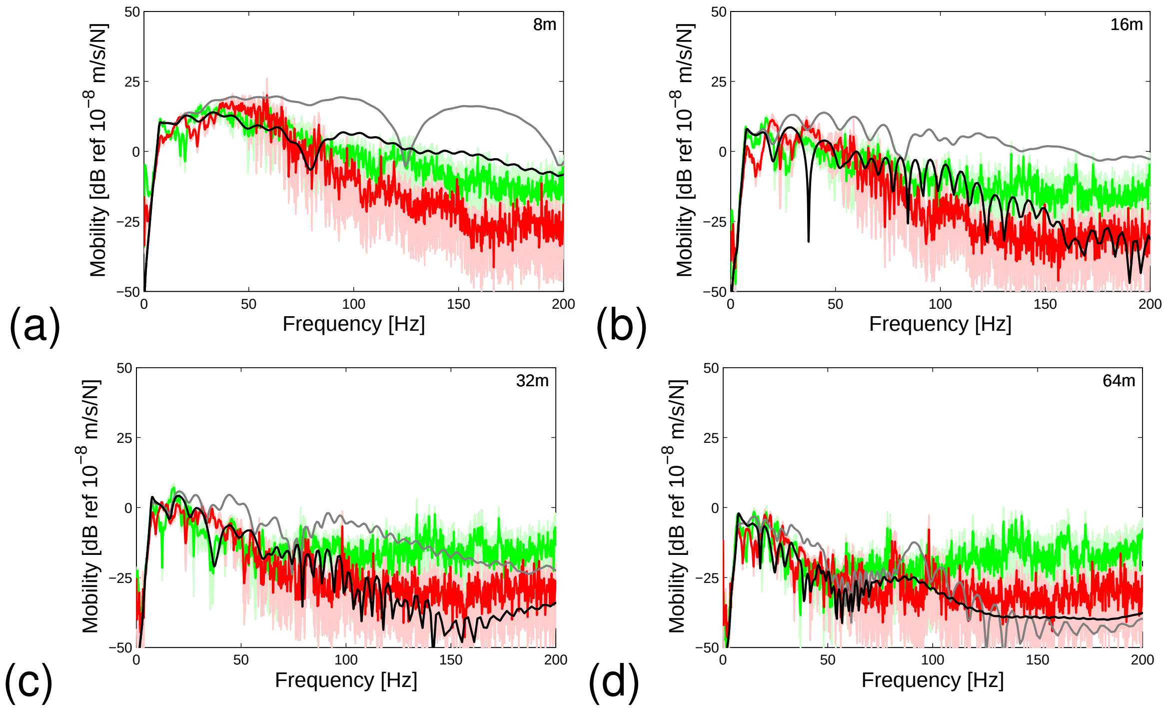
- 3D coupled finite element – boundary element method.
- Rigid foundation: finite element method.
- Layered elastic soil: boundary element formulation.

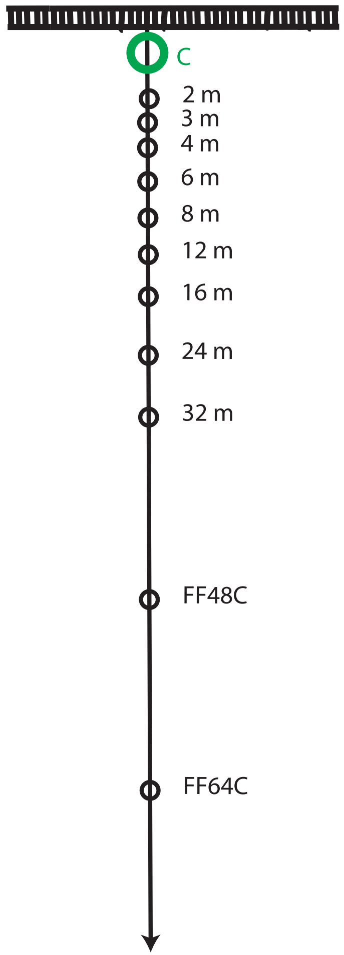


- Model and parameter uncertainty.

Free field transfer functions

- Measured and predicted transfer function (narrow band) at (a) 8 m, (b) 16 m, (c) 32 m, and (d) 64 m.
  Measured results are shown for the test (red line) and reference (green line) section. Predicted results are shown for initial (grey line) and updated (black line) soil parameters.





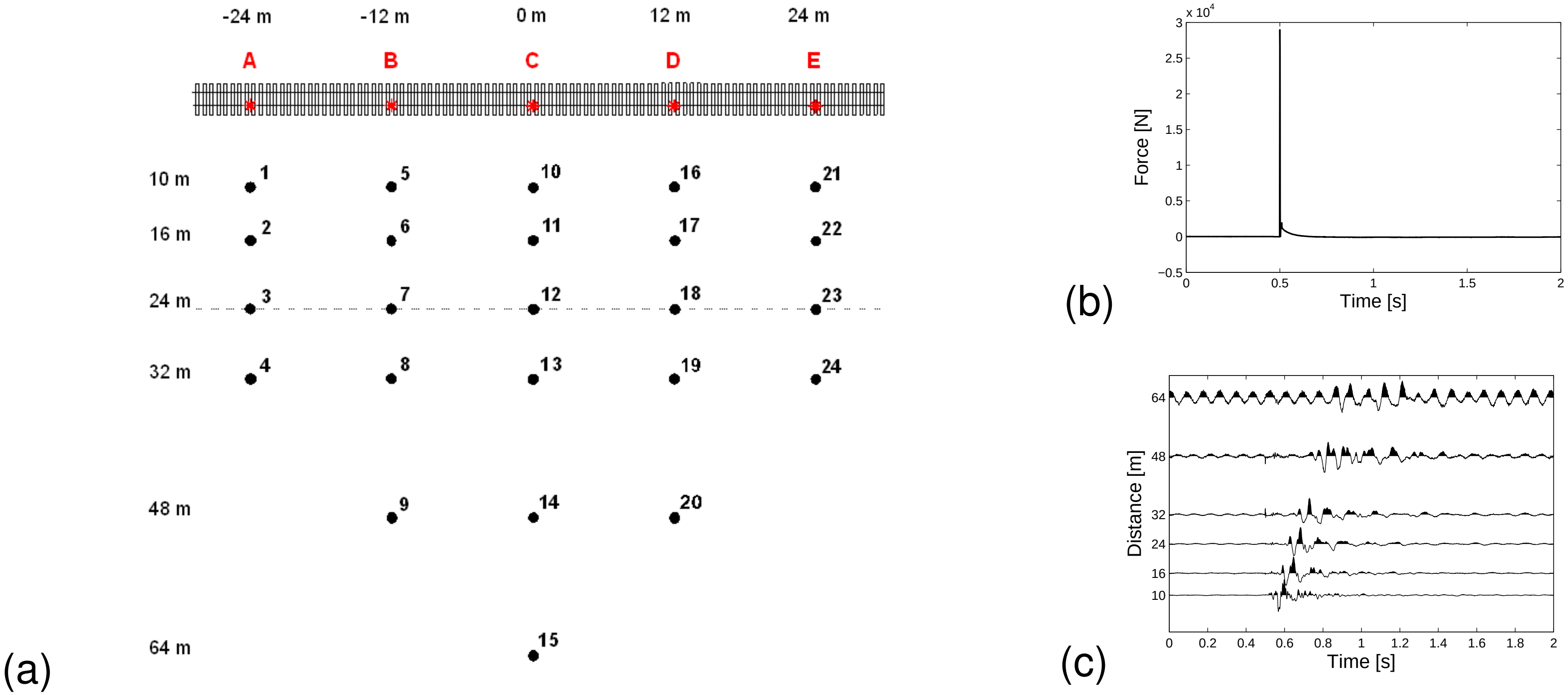
Track – free field transfer functions

Track characteristics

- RN 45 rails:
  $EI_\mathrm{r} = 3.00 \times 10^6$ Nm^2 and $\rho A_\mathrm{r} = 44.8$ kg/m.
- Bi-block reinforced concrete sleepers:
  $m_\mathrm{sl} = 200$ kg and spacing $d = 0.6$ m.
- Rubber rail pads with a thickness of 4.5 mm and stiffness of 300 kN/mm.
- Ballast layer ($d = 0.50$ m, $C_\mathrm{s} = 250$ m/s, $\nu = 0.2$ and $\rho = 1600$ kg/m^3).
- Embankment ($d = 0.50$ m, $C_\mathrm{s} = 200$ m/s, $\nu = 0.35$ and $\rho = 1700$ kg/m^3).

Measurement setup

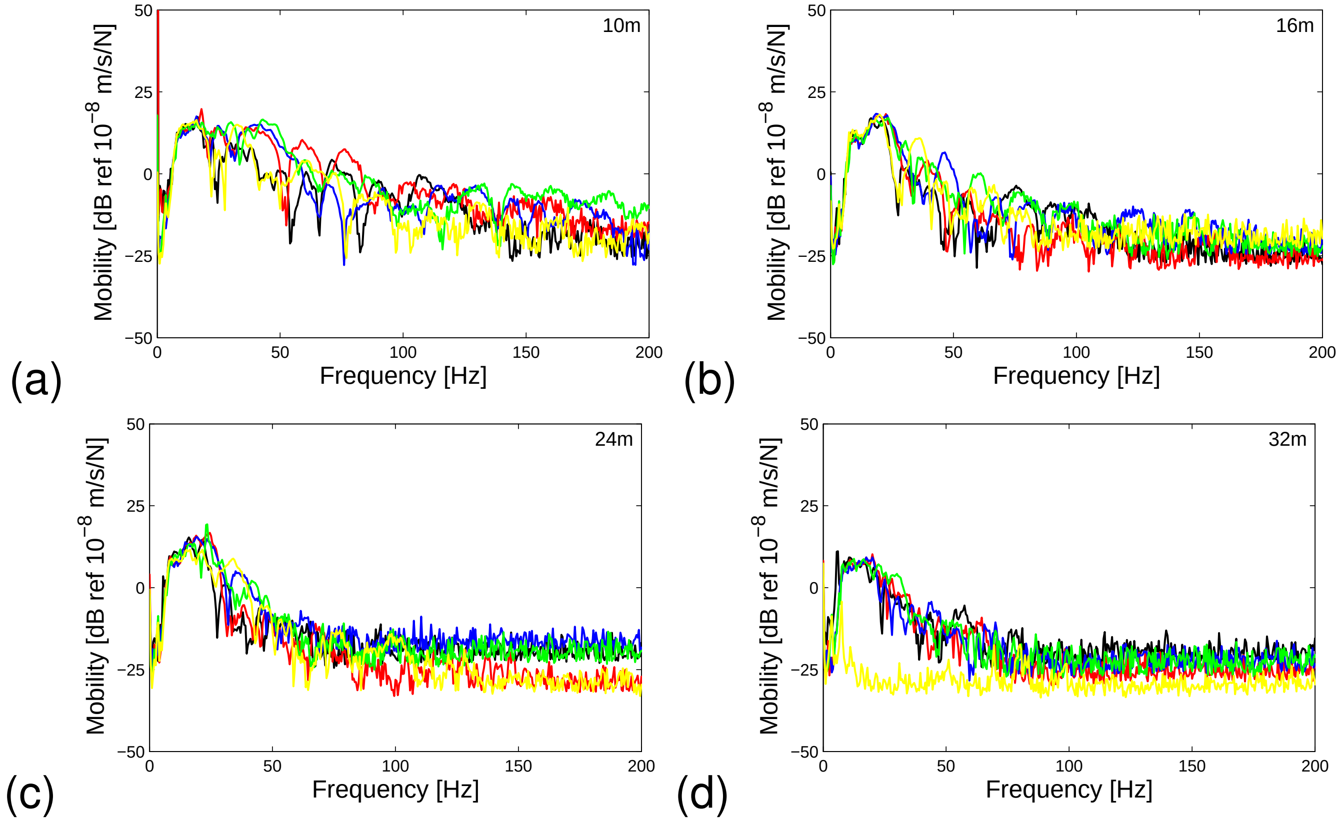
- (a) Measurement setup, (b) force during a single impact, and (c) velocity along line C stacked for 98 impacts.



Track – free field transfer functions

Variation along the track at the test section

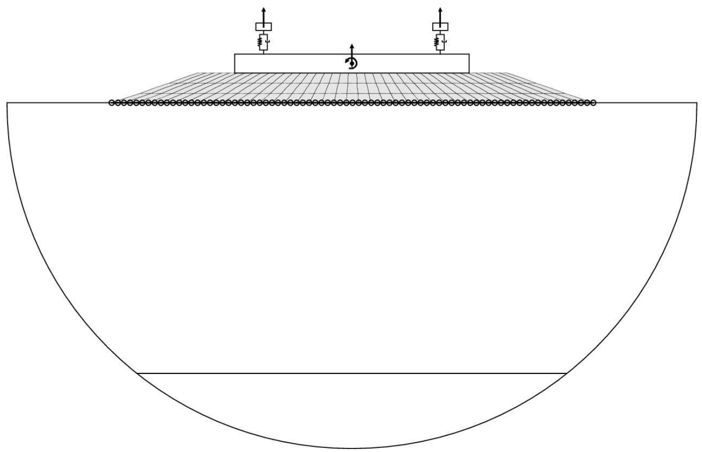
- Comparison of the free field response for all impact locations and corresponding measurement lines at (a) 10 m, (b) 16 m, (c) 24 m, and (d) 32 m from the track.



Track – free field transfer functions

Numerical model

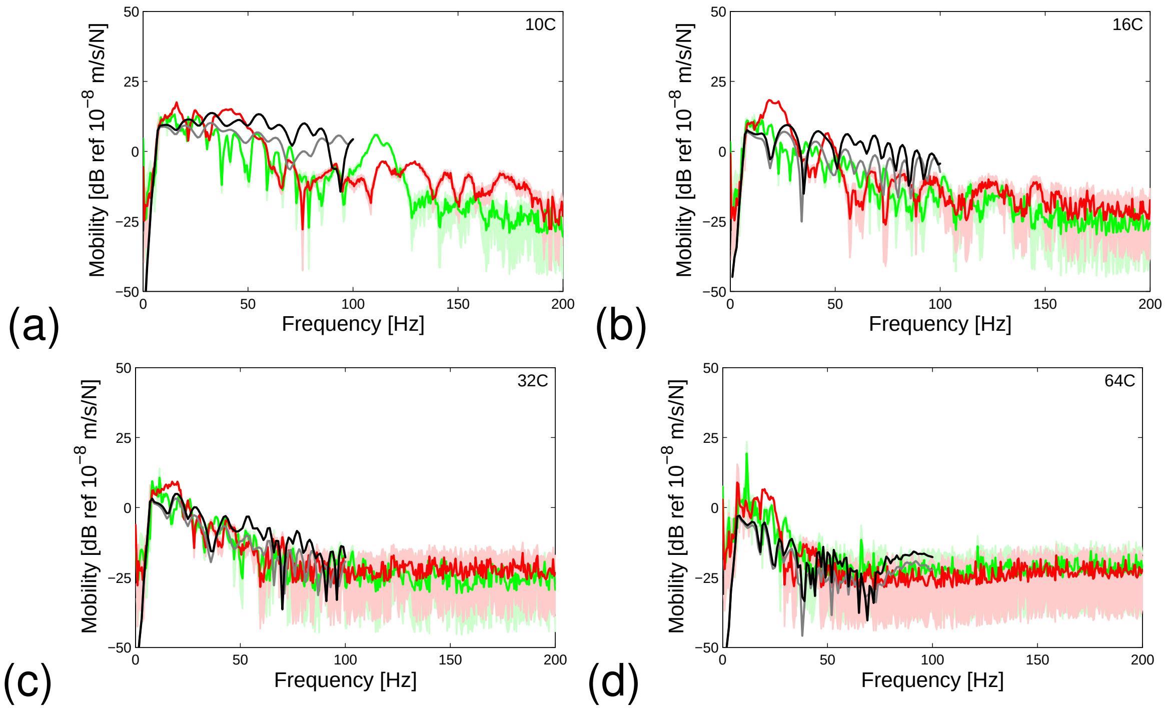
- 2.5D coupled finite element – boundary element method [François et al., CMAME, 2010].
- Track: finite element method.
  - rail and rail pad: Euler-Bernoulli beam and continuous spring-damper connection;
  - sleeper: beam, rigid in plane of cross section;
  - ballast: elastic continuum.
- Layered elastic soil: boundary element formulation.

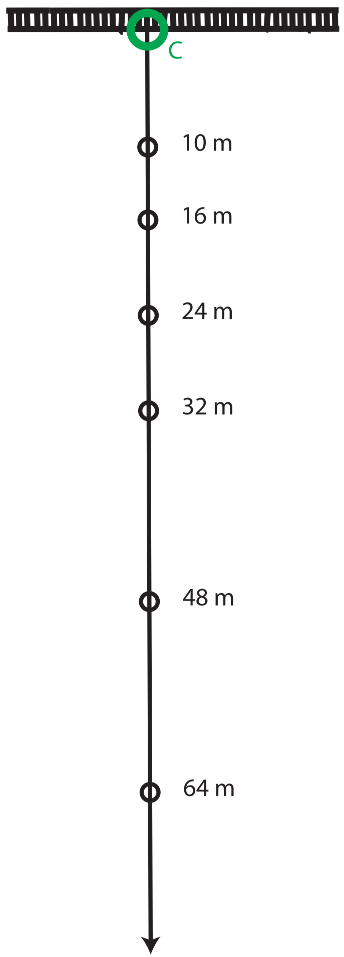


- Model and parameter uncertainty.

Transfer functions

- Measured and predicted transfer function (narrow band) at (a) 10 m, (b) 16 m, (c) 32 m, and (d) 64 m along line C. Measured results are shown for the test (red line) and reference (green line) section. Predicted results are shown for initial (grey line) and updated (black line) track parameters.





Installation of the jet grouting wall (November 2013)

Conclusion

- Determination of dynamic soil characteristics.
  - In situ geophysical techniques to determine the shear and dilatational wave velocity and material damping ratio profile.
  - Deliverable D1.1 "Test procedures for the determination of the dynamic soil characteristics" (December 2011).
  - Quantification of uncertainty on identified dynamic soil characteristics.
- Benchmark problems as a validation tool.
  - Free field and track – free field transfer functions.
  - Deliberable D1.11 "Benchmark tests for soil properties, including recommendations for standards and guidelines" (December 2013).
  - Quantification of uncertainty on model predictions.
- Assessment of vibration isolation efficiency of mitigation measures:
  - Sheet pile wall at Furet (Sweden).
  - Jet grouting wall at El Realengo (Spain).

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